Microswitch Beam Steering Grids, Final Report

Statement of the problem

Quasi-optical beam steering arrays have been previously developed using Schottky diodes at millimeter wavelengths. However, the series resistance associated with the Schottky diodes increases with the operating frequency thereby causing loss problems at millimeter and submillimeter wavelengths. The approach that was studied in this project is based on passive elements instead of active elements. The passive elements offer the advantage of low series resistance and therefore have the potential for low loss. The devices were fabricated at the Rockwell International Science Center.

The goal was to design and fabricate beam steering arrays based on micro-electro-mechanical-systems (MEMS) at millimeter wavelengths (35 and 94 GHz). Figure 1 shows the principle of a transmission-type beam steering approach. The beam steerer is assembled as a stack of silicon wafers separated by free space. An incident wave enters the grid from the left side, passes through several layers of phase shifters, and then reradiates from the right side into free-space. Each phase shifting layer is a grid of switches which represents either inductive (closed switch) or capacitive (open switch) reactances. Proper free-space electrical lengths between the wafers and the layout of the array are adjusted to minimize the reflection loss. The number of the layers used in the array determines the steering resolution, and the direction of the beam is set by the initial settings of the binary switches.
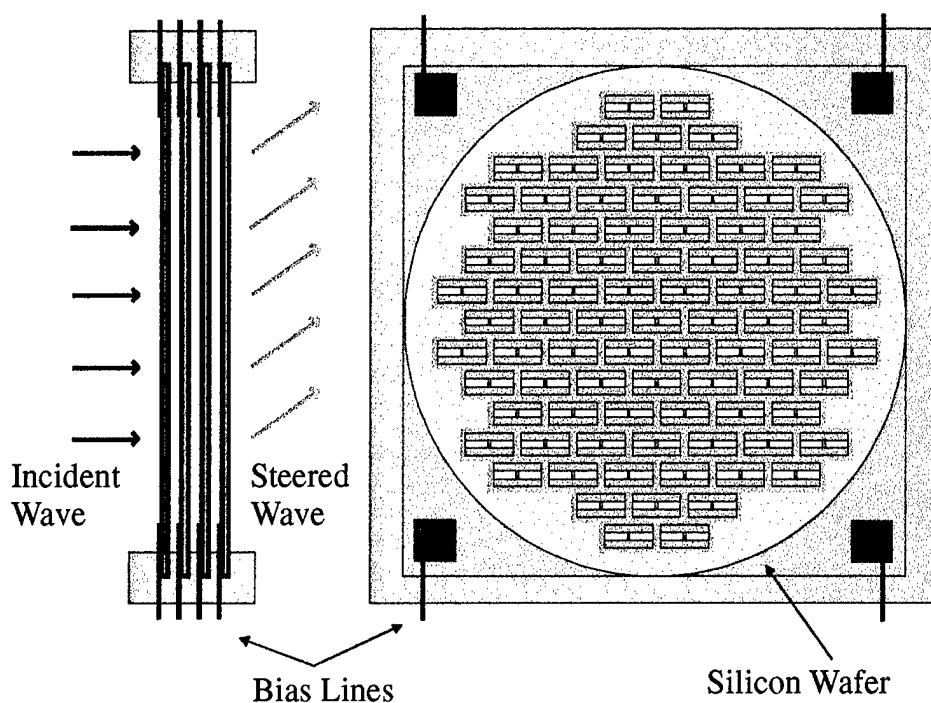

Incident Wave

Steered Wave

Bias Lines

Silicon Wafer

Figure 1. Transmission-type beam steering

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Summary of the most important results

The first structures

The first structure attempted is reported in the Ph.D. thesis of Jung-Chih Chiao [1]. The next design was proposed by Ken-Ichiro Natsume [2] at the California Institute of Technology. Figure 2 shows the unit-cell waveguide model which originates from these first designs [3]. Ansoft's HFSS has been used for analyzing the arrays. The model is based on utilizing E- and H-plane symmetry, and analyzing a quarter of a unit cell. In practice, this is analogous to an infinite array having a uniform (plane wave) illumination.
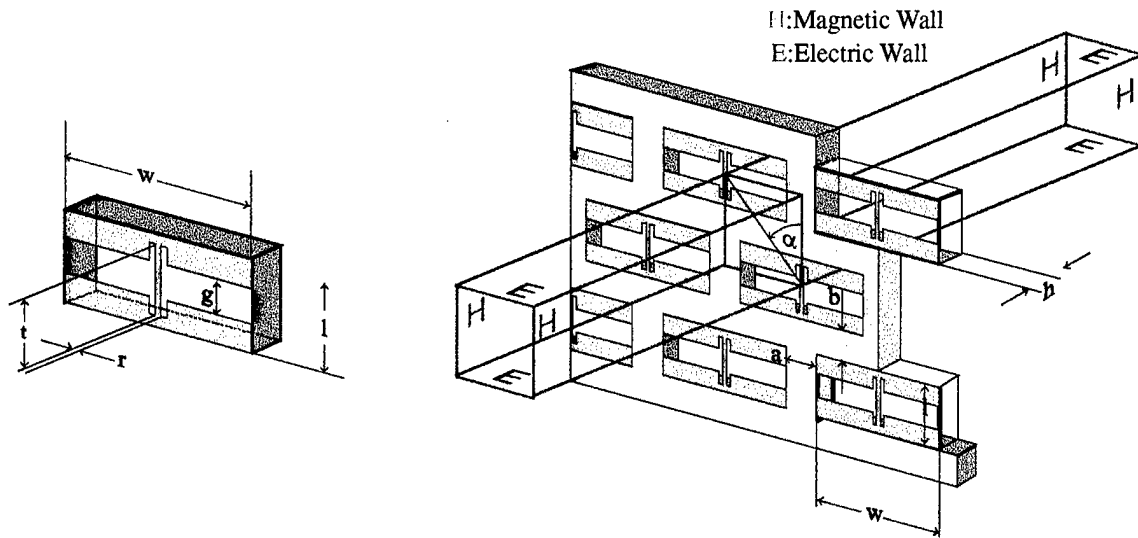

Figure 2. Unit-cell waveguide model. Inductive array corresponds to the ON state of the switch.

Current design

Current designs for 35 and 94 GHz were done by Polly Preventza. The designs were based on the unit-cell waveguide model and Ansoft's HFSS and circuit models were used in the analyses. In the 94 GHz design, 1 μm thick Si_3N_4 membrane and a 254 μm thick silicon wafer were used. The 35 GHz design was done by scaling the dimensions of the 94 GHz design. The designs and measurements of the passive structures are extensively reported in [3] and briefly summarized in [4].

Fabrication procedures

There are several processing challenges in fabricating these structures. One challenge is the protection of the front side MEM structure during back side substrate removal. Another is making the final membrane flat after many processing steps involved in the fabrication. Finally, rigidity of the membrane is required in this application. Wet and dry substrate etches with a dielectric (Si_3N_4) were able to produce passive structures but not able to produce operating switches. The most promising technology is a dry etch with a silicon membrane which is capable

of producing operating switches. The various fabrication technologies are more thoroughly reported in [3].

However, experiments done at the Rockwell Science Center on this kind of devices shows that there is generally an increase in device non-planarity with time, due to increases in both the microstructure metal stress and oxide stress gradients. The physical mechanism for these changes are unknown, and they are currently under study at Rockwell.

Passive arrays with 6 μm Si/SiO$_2$ membrane

These arrays have been designed for 94 GHz [3]. However, the array structure has not been optimized for the 6 μm Si/SiO$_2$ membrane. The optimum operating frequency of the capacitive pair is 75 GHz or less. This is similar behavior to the capacitive array, which has the 1 μm Si$_3$N$_4$ membrane. The down-shifted resonant frequency is due to the membrane. The membrane should be included in the future designs. Figure 3 shows a comparison between the inductive pair and the capacitive pair. In this case, the spacing between the inductive arrays has been tuned in order to minimize the loss at the low end of the W-band. The loss of the inductive pair is approximately 2 dB in the range of 75–90 GHz. The loss of the capacitive pair is about 4 dB at 77 GHz. The phase difference between these pairs is about 125° in the range of 75–90 GHz. These results are more thoroughly reported in [4].
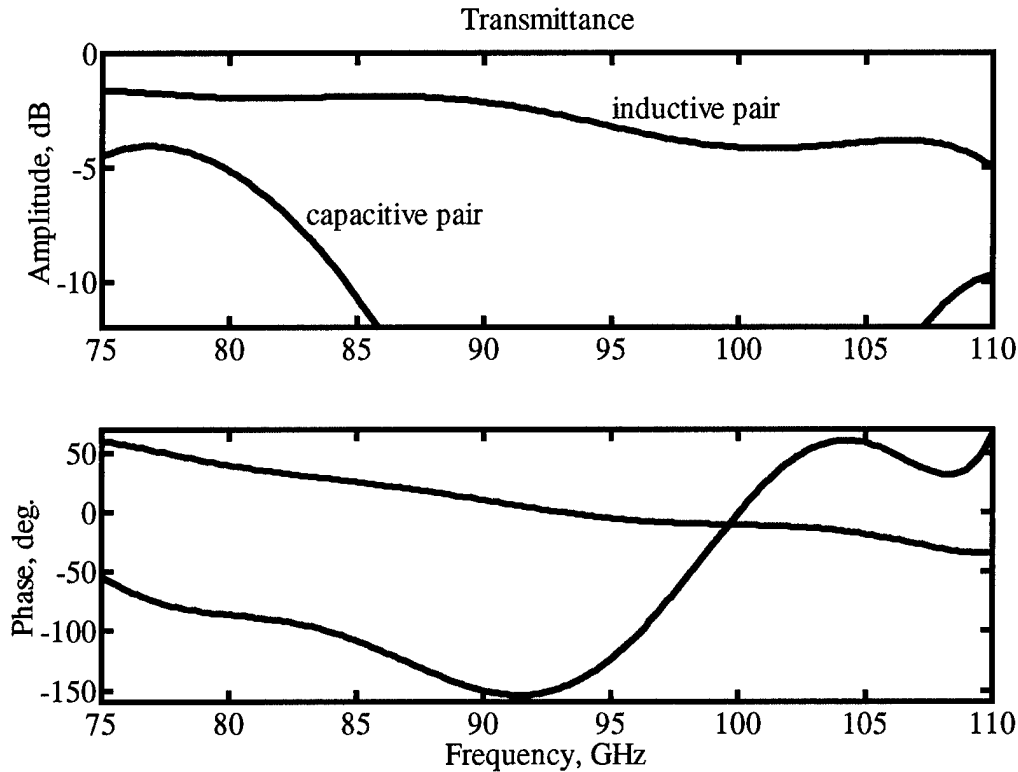

Figure 3. Comparison between an inductive pair and a capacitive pair.

Comparison between theoretical and experimental results

Ansoft's HFSS has been used for analyzing the arrays with the with the 6 μm Si/SiO$_2$ membrane. The dimensions used in the HFSS model are those measured from the array under a microscope and they are shown in Figure 4. For the conductivity of gold $\sigma = 3 \times 10^7$ S/m was used. Figure 5 shows a comparison between the HFSS result and three different measurement results of the inductive array. In the measurements, the spot size of the gaussian beam was varied between 6–22 mm. Figure 6 shows the corresponding results for the capacitive array. Bigger spot size gives more uniform illumination for the array and, therefore, it matches better with the theoretical results where a uniform illumination is assumed. The agreement between the theoretical and measured results is good.
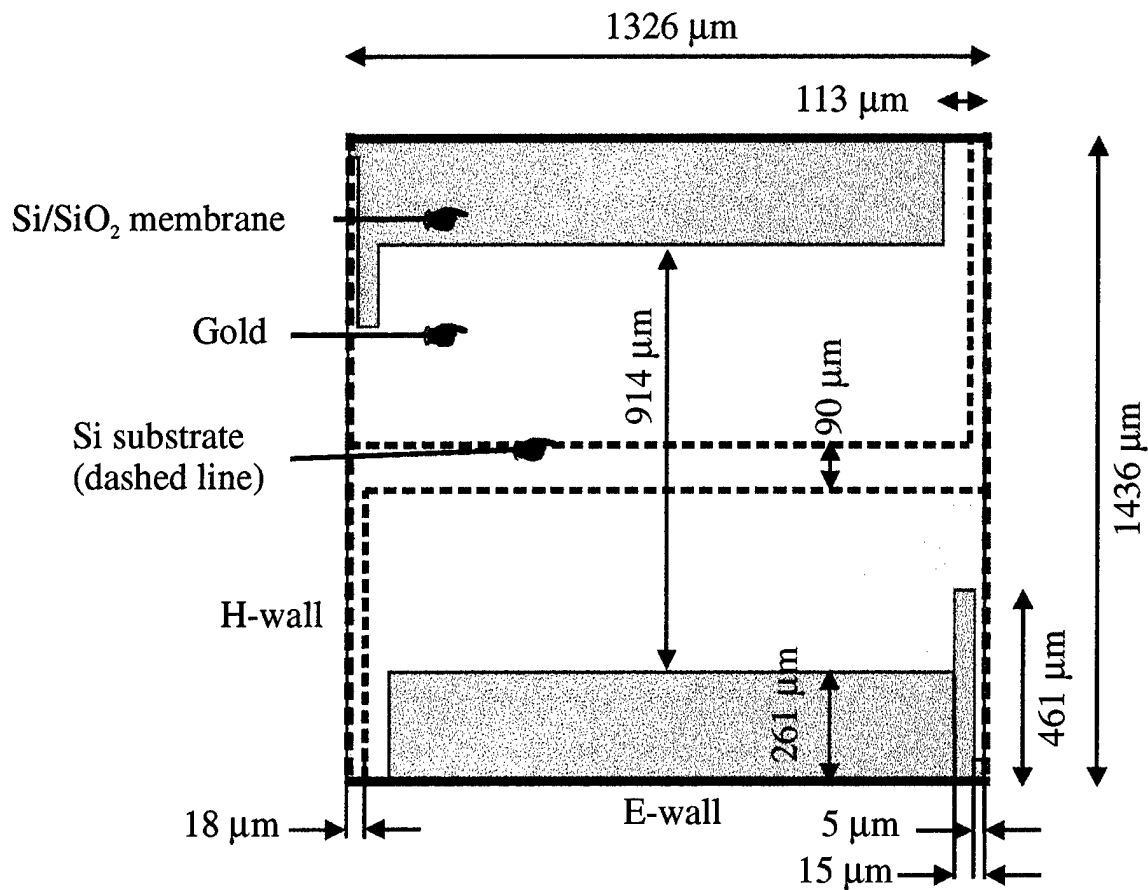

Figure 4. HFSS model for a quarter unit-cell that was used in the simulation.
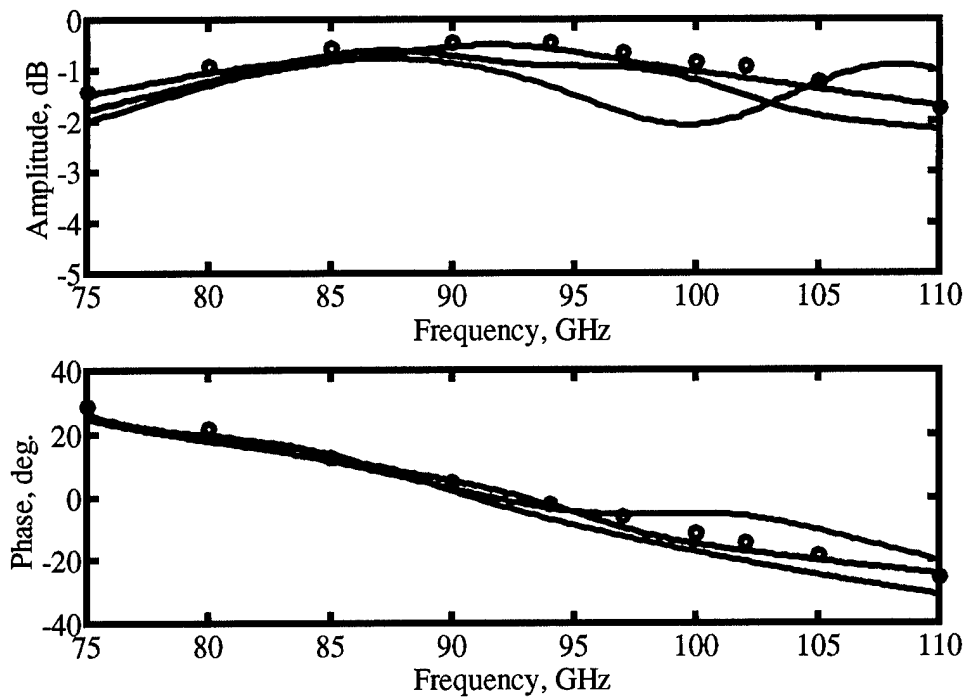
Figure 5. Comparison between HFSS (red circles) and measurements of inductive array: 6 mm spot (green), 16 mm spot (blue), and 22 mm spot (red).
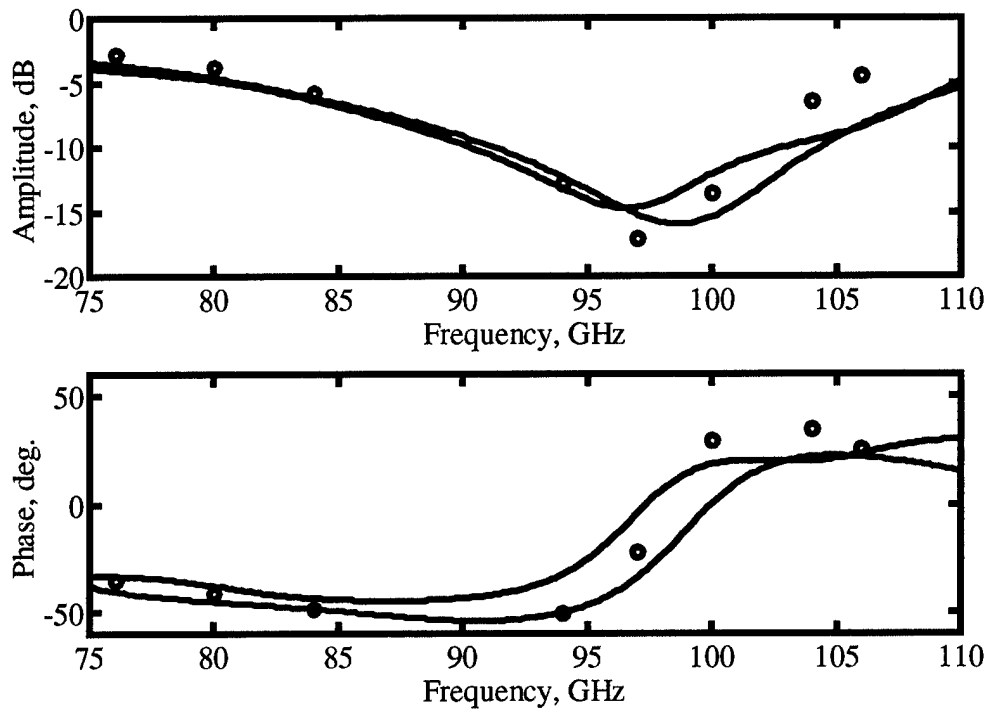

Figure 6. Comparison between HFSS (red circles) and measurements of inductive array: 6 mm spot (blue) and 22 mm spot (red).

Switches

DC testing at Rockwell Science Center

Switches were dc-tested using a probe station at Rockwell Science Center. This testing was done by optical observation of the structure. Switches were observed to actuate at about 70 V for about 10 operations. Two of the arrays were considered to be very good, where nearly all metal lines from bias pads to the switches were intact. One was considered to be good with only some metal lines broken. Three arrays were poor with many or nearly all metal lines broken.

Mounting and RF testing at Caltech

The arrays with operating switches were mounted on glass plates which had an appropriate metal (gold) pattern on top of them for the bias, Figure 7. The glass plates had a hole in the center so that the millimeter wave beam would only propagate through the array, not the glass. At first, crystal bonding was used for mounting the wafers, but that required heating the glass plate up to about 80°C, which may cause mechanical stress on the array when the glass plate is cooling down. This was tested with two poor arrays and one good array: in one array, the wafer was slightly fractured. Eventually, vacuum grease was used for mounting the arrays in order to avoid any mechanical stress. By the time of the mounting, the cantilever arms showed increased deflection upwards compared to the original deflection.

Wedge bonder was used for the necessary wire bonding. The switches turned out be very fragile, and most them were broken. Some switches fractured during bonding. Other switches broke during actuation. About one half of the switches in one grid were not broken, but this grid had poor wiring. As a conclusion, the switches could not be closed, and only open switches were tested with similar results to those of capacitive grids. Figure 8 shows an example of a broken switch.

Further tests at Rockwell Science Center

The remaining switches were tried to actuate using electrical connections from probe station tips, and the devices broke upon this attempted actuation. By this time the cantilever arm tip deflection was 6–7 μm, which is clearly more than soon after the release. It seems that during the deflection from actuation, the switch microstructures exhibit stresses greater than the yield stress, because of the increased non-planarity.
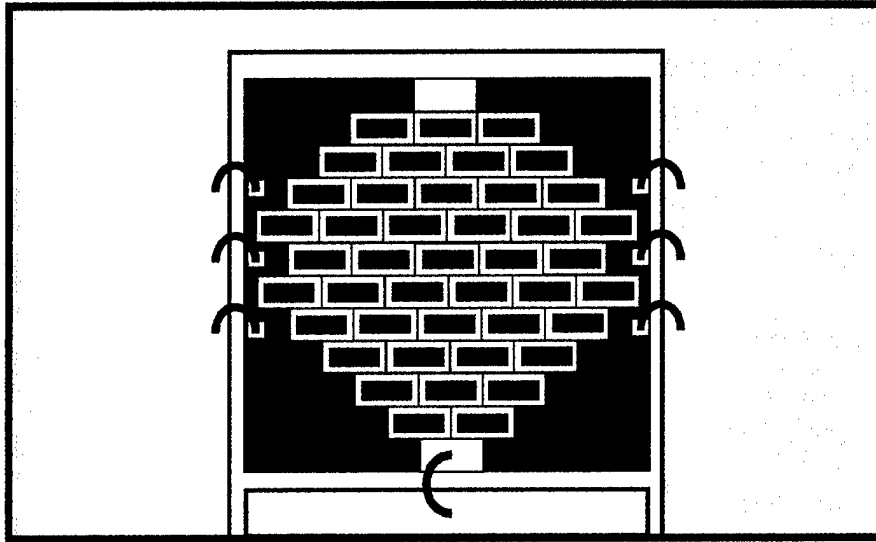
Figure 7. Grid on top of a gold plated glass plate. Only six of the 43 dc-bias pads are shown. Thin wiring from bias pads to switches and the switches are not shown.
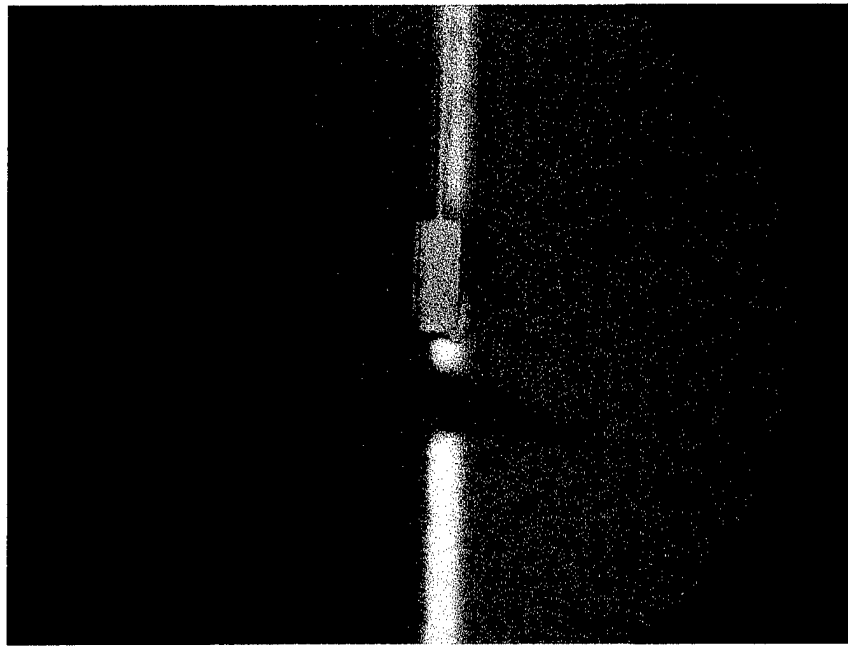

Figure 8. Example of a broken switch.

Conclusions

94 GHz passive grids have been analyzed and tested. The most promising fabrication method at the moment is dry substrate etch with silicon membrane. The current design was done assuming zero-thickness for the dielectric membrane [3], which is a sound approximation if the membrane is very thin (less than 1 μm). Thicker silicon/silicon dioxide membrane was used in order to make operating switches (6 μm). The effect of the finite-thickness membrane is to shift down the

operating frequency, especially in the case of the capacitive arrays. The measured phase performance of the arrays was very good at 75–90 GHz. Good agreement between the measured and simulated transmittances was found, when the finite thickness of the membrane was included in the analysis. Future arrays should be designed by taking the thickness of the membrane into account.

At the time of the mounting and testing, the cantilever arms showed increased deflection upwards compared to the original deflection. Some switches fractured during bonding. Other switches broke during actuation, and hence, RF switching tests could not be performed. Experiments done at the Rockwell Science Center on this kind of devices shows that there is generally an increase in device non-planarity with time, due to increases in both the microstructure metal stress and oxide stress gradients. The physical mechanism for these changes are unknown, and they are currently under study at Rockwell. These fabrication issues must be resolved before this approach becomes practical.

List of publications and technical reports

1. J.-C. Chiao, "Quasi-Optical Components for Millimeter and Submillimeter Waves," *Ph.D. Thesis*, California Institute of Technology, Pasadena, CA, 1996.
2. K.I. Natsume, D.B. Rutledge, A. Higgins, R. Mihailovich, "Microswitch Beam Steering Grids," *Report prepared for the ARO,* June 1997.
3. P. Preventza, "Analysis and Design for Quasi-Optical Structures," *Ph.D. Thesis*, California Institute of Technology, 1999.
4. T. Hirvonen, D.B. Rutledge, "Microswitch Beam Steering Grids," *Report prepared for the ARO,* October 1999.
5. T. Hirvonen, D.B. Rutledge, "Microswitch Beam Steering Grids," *Report prepared for the ARO,* December 1999.

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J.-C. Chiao, Graduate Student, Ph.D. Thesis, 1996.

K.I. Natsume, Visiting Associate.

P. Preventza, Graduate Student, Ph.D. Thesis, 1999.

T. Hirvonen, Post-Doctoral Scholar.

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13. ABSTRACT (Maximum 200 words)

The goal was to design and fabricate beam-steering arrays based on micro-electro-mechanical-systems (MEMS) at millimeter wavelengths (35 and 94 GHz). The design was based on a unit-cell waveguide model, and HFSS was used in the theoretical analyses. Dry substrate etch with a Si/SiO_2 membrane was found to be the most promising fabrication technology. Rockwell Science Center manufactured the arrays. The measured passive structures show a good performance. The phase difference between an inductive and a capacitive pair is about 125° at a frequency range of 75–90 GHz. The average loss at 77 GHz is about 3.2 dB. Good agreement between theoretical and experimental results was found.

Rockwell has had difficulties in fabricating the microswitch arrays. A major difficulty has been fabrication of switches on membrane. The switches have showed an increased deflection upwards with time. Some switches fractured during wire bonding. Other switches broke during actuation. These fabrication issues must be resolved before this approach becomes practical.

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